Constraints on stellar yields and SNe from gamma-ray line observations

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Abstract

Gamma-ray line observations provide a versatile tool for studies of nucleosynthesis processes and supernova physics. In particular, the observation of radioactive species in the interstellar medium probes recent nucleosynthesis activity on various time-scales for different kinds of sources. Considerable progress in gamma-ray instrumentation during the last decades has led to the discovery of several cosmic gamma-ray lines. In this review, recent observational results are presented and their astrophysical implications are discussed. Prospects of gamma-ray line astronomy will be explored in view of the future INTEGRAL mission.

Key words: Gamma-ray astronomy; nucleosynthesis; supernovae; chemical evolution

1 Introduction

During the last decade the field of gamma-ray line astronomy has made important progress. On the one hand, the explosion of the nearby supernova SN 1987A in the Large Magellanic Cloud provided us with a bright source of nuclear gamma-ray lines due to the decay of freshly produced radioactive isotopes. On the other hand, a new generation of space borne telescopes, such as COMPTEL and OSSE on the *Compton Gamma-Ray Observatory*, and TGRS on *WIND*, provided for the first time sufficient sensitivity, angular and spectral resolution for a comprehensive study of galactic gamma-ray lines. Still, gamma-ray line astronomy is plagued by a dominating instrumental background, induced by cosmic-ray bombardment in the hostile space environment, reducing line detections to significancies below typically $5 - 10\ \sigma$. Consequently, uncertainties on observed line fluxes or profiles are still quite important. Nevertheless, the available observational material is continuously

growing, starting to provide interesting constraints on nucleosynthesis processes.

Most gamma-ray lines are produced in desexcitation transitions between nuclear levels. These gamma-ray lines may be subdivided into 2 categories that are defined by the channel that led to the nuclear excitation: (a) radioactive decay into an excited state of the daughter isotope, or (b) nuclear interactions and reactions. Radioactive decays are eventually accompanied by positron emission, resulting in a 511 keV gamma-ray line from e^+e^- annihilation. Other mechanisms leading to positron production involve compact objects, where high densities or strong magnetic fields favour e^+e^- pair production.

2 Radioactivity lines

Gamma-ray lines from radioactivities demand several conditions to be observable. First, a hot and dense medium with sufficiently low entropy is required to allow for the synthesis of fresh radioisotopes. Such a medium can be found in stellar interiors, at the base of the accreted envelope of white dwarfs in close binary systems, or even in accretion disks around compact objects. The nuclear reaction networks in operation are characteristic for the composition, density, and temperature at the burning site, hence the observation of isotopic abundance patterns provide direct insight into the nucleosynthesis conditions. Second, the fresh radioisotopes have to be removed quickly from the formation site to prevent destruction by nuclear reactions or natural decay. This generally implies convection followed by mass ejection, either in form of stellar winds or explosions, and requires lifetimes of at least several days, better several months. Additionally, nucleosynthesis sites are generally optical thick to gamma-rays, hence escape of the radioisotopes to optically thin regions is mandatory for gamma-ray line observations. Consequently, radioisotopes can probe stellar convection and ejection processes, providing important information about the involved stellar physics. Third, the lifetime has to be short enough and the abundance of the isotope has to be high enough to assure a sufficient radioactive decay activity that is in reach of modern gamma-ray telescopes.

These constraints result in a list of candidate isotopes that may actually be accessible to gamma-ray line astronomy (cf. Table 1). The observation of radioactivity lines implies various time-scales. For lifetimes that are short compared to the event frequency (^{57}Ni - ^{57}Co), individual *transient* gamma-ray line sources are expected, mainly in form of supernovae or novae. For lifetimes of the order of the event frequency (^{22}Na - ^{44}Ti) several rather steady gamma-ray line sources are expected in from of supernova remnants or recent nova events. For lifetimes that are long compared to the event frequency (^{26}Al -

Table 1
Gamma-ray lines from radioactivities that may be accessible to gamma-ray astronomy (ordered by ascending lifetime). Theoretical nucleosynthesis yield estimates are quoted for different source types. Positron emitters are marked by †.

Isotope	Lifetime τ	Lines (keV)	Typical yields ($M_\odot$)				
			WR	SN Ia	SN Ib/c	SN II	Nova
^{57}Ni	2.14 d	1378		0.02	$5\,10^{-3}$	$5\,10^{-3}$	
^{56}Ni	8.5 d	158, 812		0.5	0.1	0.1	
^{59}Fe	64.2 d	1099, 1292			$5\,10^{-5}$	$5\,10^{-5}$	
^{7}Be	77 d	478			10^{-7}	$5\,10^{-7}$	$5\,10^{-11}$
^{56}Co†	112 d	847, 1238		0.5	0.1	0.1	
^{57}Co	392 d	122		0.02	$5\,10^{-3}$	$5\,10^{-3}$	
^{22}Na†	3.76 yr	1275		10^{-8}	10^{-6}	10^{-6}	$5\,10^{-9}$
^{60}Co	7.61 yr	1173, 1333			10^{-5}	10^{-5}	
^{44}Ti†	87 yr	1157		10^{-5}	$5\,10^{-5}$	$5\,10^{-5}$	
^{26}Al†	10^6 yr	1809	10^{-4}		$5\,10^{-5}$	$5\,10^{-5}$	10^{-8}
^{60}Fe	$2.2\,10^6$ yr	1173, 1333		$5\,10^{-3}$	$5\,10^{-5}$	$5\,10^{-5}$	

^{60}Fe) a superposition of numerous individual gamma-ray line sources will lead to a diffuse glow of gamma-ray line emission. Additionally, the radioisotopes may travel considerable distances away from the production sites before they decay ($\sim 10 - 100$ pc), leading to intrinsically extended sources. Hence, diffuse galaxywide emission is expected for ^{26}Al and ^{60}Fe (see [27,6] for recent reviews).

2.1 SN 1987A - a nucleosynthesis laboratory

The explosion of SN 1987A in the Large Magellanic Cloud was a great opportunity for gamma-ray line astronomy. For the first time, a supernova explosion occurred close enough to be in reach of available gamma-ray telescopes. During core collapse, substantial amounts of ^{56}Ni and ^{57}Ni are produced which subsequently decay under gamma-ray lines emission to ^{56,57}Co and finally to ^{56,57}Fe (cf. Table 1). The production of these isotopes in supernova explosions has been indirectly inferred from lightcurve characteristics, reflecting the respective decay times. The direct observation of the gamma-ray lines from ^{56}Co [23] and ^{57}Co [19] in SN 1987A was a brilliant confirmation of this interpretation. The observed relative intensities of the gamma-ray lines from ^{56}Co and ^{57}Co

indicated a ^{57}Ni/^{56}Ni ratio between $1.5-2$ times the solar ratio of ^{57}Fe/^{56}Fe, consistent with core collapse supernova models [34].

Surprisingly, the ^{56}Co lines were detected already 6 months after explosion, at an epoch where standard onion-shell supernova expansion models still predicted a substantial gamma-ray opacity for the envelope. The gamma-ray line lightcurves presented clear evidence that ^{56}Co was found over a large range of optical depths, with a small fraction at very low depth [20]. Probably some fragmentation of the ejecta and acceleration of the emitting radioactivity within are required to explain the observations. The acceleration hypothesis is supported by various gamma-ray line profile measurements all indicating line widths of order 1 % FWHM, corresponding to Doppler velocities of 3000 km s^{-1} [22,29,32].

Measurements of the bolometric SN 1987A lightcurve indicate that also some ^{44}Ti has been produced during the explosion. The expected 1.157 MeV gamma-ray line intensities are actually too weak for current telescopes, but the decay of ^{44}Ti is sufficiently slow that it will be observable by future, more sensitive instruments. Hence, SN 1987A still remains an interesting nearby laboratory for studies of explosive nucleosynthesis processes.

2.2 ^{44}Ti - unveiling recent supernova

The census of recent galactic supernova events is exclusively based on historic records of optical observations and amounts to 6 events during the last 1000 years. Due to galactic absorption and observational bias, this census is by far not complete. Gamma-ray line observations of the ^{44}Ti isotope have the potential to considerably increase the statistics. ^{44}Ti is believed to be exclusively produced by supernova events, and its production can be inferred from the solar abundance of the decay product ^{44}Ca. Due to the penetrating power of gamma-rays, ^{44}Ti lines from recent supernova events throughout the Galaxy can reach the Earth, and therefore unveil yet unknown young supernova remnants.

The prove of principle was recently achieved by the first observation of a 1.157 MeV gamma-ray line from the 320 years old Cas A supernova remnant using the COMPTEL telescope [9]. Note that Cas A almost escaped visual detection if it were not accidentally included in Flamsteed's sky atlas as a star of 6th magnitude. This fact is indeed very puzzling since nucleosynthesis models predict large amounts of ^{56}Ni being co-produced with ^{44}Ti, which would have resulted in a visual peak magnitude of -4^m for Cas A. Although a possible extinction of 10 mag could solve this problem, it is yet to be confirmed observationally. Alternative explanations invoke ionisation of ^{44}Ti or

an asymmetric explosion. Ionisation would prevent ^{44}Ti decaying by orbital electron capture and hence falsify the relation between observed gamma-ray line flux and present ^{44}Ti mass, relaxing the constraint on the amount of ^{56}Ni produced during the explosion [24]. An asymmetric explosion could increase ^{44}Ti over ^{56}Ni production in the high entropy alpha-rich freezeout along the polar directions [25].

Evidence for another galactic ^{44}Ti source was recently found in the Vela region where no young supernova remnant was known before [10]. Triggered by this discovery, a re-analysis of ROSAT X-ray data indeed revealed a spherical structure at the position of the new ^{44}Ti source, now identified as the RX J0852.0-4622 supernova remnant [2]. Although the ^{44}Ti observation is only marginal [30], it is the first time that gamma-ray line observations triggered the discovery of a new supernova remnant. Again, no optically bright display has been recorded for RX J0852.0-4622 – are ^{44}Ti producing supernovae optically faint (or obscured)?

2.3 ^{26}Al - recent galactic star formation history

Intense galactic gamma-ray line emission at 1.809 MeV, attributed to the radioactive decay of ^{26}Al, has been reported by numerous instruments (see [27] for a review). In principle, ^{26}Al could be produced in appreciable amounts by a variety of sources, such as massive mass losing stars (mainly during the Wolf-Rayet phase), Asymptotic Giant Branch stars (AGBs), novae (mainly of ONe subtype), and core collapse supernovae. Considerable uncertainties that are involved in the modelling of nucleosynthesis processes, mainly due to the poorly known physics of stellar convection, do not allow for a theoretical determination of the dominant galactic ^{26}Al sources.

The 1.809 MeV gamma-ray line has now for the first time being imaged using the COMPTEL telescope [14,5,26,17]. The COMPTEL image shows an intense, asymmetric ridge of diffuse galactic 1.809 MeV emission with a prominent localised emission enhancement in the Cygnus region (cf. Fig. 1). Additional hints for emission peaks along the galactic plane can be understood as fingerprints of the galactic spiral pattern. Globally, the distribution of 1.809 MeV gamma-ray line emission follows very closely the distribution of galactic free-free emission [18]. Since galactic free-free emission is an excellent tracer of the massive star population ($M_i > 20\ M_{\odot}$), the close correlation suggests that ^{26}Al is mainly produced by this population [16]. Consequently, due to the short lifetime of massive stars, ^{26}Al becomes an excellent tracer of recent galactic star formation.

The radial ^{26}Al mass density distribution illustrates that the bulk of galac-

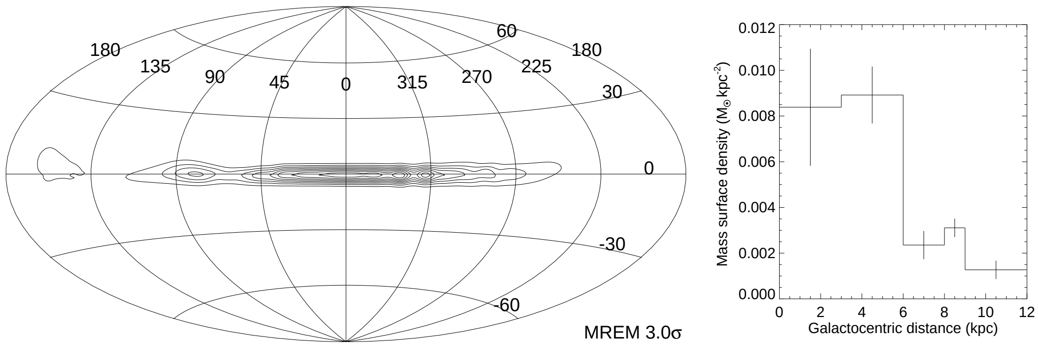

Fig. 1. *Left:* COMPTEL 1.809 MeV gamma-ray line allsky map [17]. *Right:* Radial ^{26}Al mass density profile [15].

tic star formation occurs at distances of less than 6 kpc from the galactic centre (cf. Fig. 1). Star formation is also present within the central 3 kpc of the Galaxy, although at a poorly determined rate. There are indications for enhanced star formation between $3-6$ kpc, coinciding with the molecular ring structure as seen in CO data [4]. Enhanced star formation is also seen in the solar neighbourhood ($8-9$ kpc) which probably corresponds to the local spiral arm structure. However, the radial ^{26}Al profile is probably not directly proportional to the radial star formation profile since ^{26}Al nucleosynthesis may depend on metallicity. It will be important to determine this metallicity dependence in order to extract the true star formation profile from gamma-ray line data. Valuable information about the metallicity dependence will come from a precise comparison of the 1.809 MeV longitude profile to the profile of free-free emission [16]. Additionally, observations of gamma-ray lines from ^{60}Fe, an isotope that is only believed to be produced during supernova explosions, can help to distinguish between hydrostatically and explosively produced ^{26}Al, and therefore help to disentangle the metallicity dependencies for the different candidate sources.

3 Annihilation line

The 511 keV gamma-ray line due to annihilation of positrons and electrons in the interstellar medium has been observed by numerous instruments (see [8] and references therein). At least two galactic emission components have been identified so far: an extended bulge component and a disk component. Indications of a third component situated above the galactic centre have been reported [28,8], yet still needs confirmation by more sensitive instruments.

The galactic disk component may be explained by radioactive positron emitters, such as ^{26}Al, ^{44}Sc, ^{56}Co [21]. Although all these isotopes are also gamma-ray line emitters, only ^{26}Al will lead to correlated gamma-ray line and 511 keV

emission since the typical annihilation time scale of some 10^5 yrs considerably exceeds the lifetime of the other isotopes. Consequently, 511 keV line-emission is a potential tracer of extinct short-lived galactic radioactivities.

The origin of the galactic bulge component is much less clear. Reports of time-variable, possibly red-shifted 511 keV line features from the galactic centre direction led to the idea of compact objects being responsible for the galactic bulge component [21]. However, recent observations using more sensitive instruments could not confirm any time-variability [12,31,8,3]. Actually, the most plausible source of the galactic bulge component may also be extinct short-lived radioisotopes from an old stellar population with a prominent galactic bulge component. Type Ia supernovae could be good candidates for such a population since they produce appreciable amounts of ^{56}Co (a positron emitter) and they are believed to belong to the old stellar population. Hence it may turn out that the 511 keV annihilation line is an excellent tool fur studies of the galactic SN Ia population.

Some information about the annihilation environment is obtained from 511 keV line shape measurements and the determination of the positronium fraction. In fact, positrons and electrons may eventually form a short-lived hydrogen-like system called positronium which decays either into two 511 keV photons or a three photon continuum below 511 keV. The relative intensities of both components carry information about the fraction f of annihilations via positronium formation, probing the thermodynamic and ionisation state of the annihilation environment [7]. Recent observations suggest a positronium fraction of $f = 0.9 - 1.0$ for the galactic bulge component [13,8]. Together with the only moderately broadened 511 keV line width, this indicates that annihilation mainly occurs in the warm neutral or ionised interstellar medium [8].

4 Perspectives

Due to continuing progress in instrumentation, the field of gamma-ray line astronomy has now become a new complementary window to the universe. With the COMPTEL and OSSE telescopes on *CGRO*, the entire sky has been imaged for the first time in the light of gamma-ray lines, leading to maps of 511 keV annihilation radiation and ^{26}Al 1.809 MeV emission. New gamma-ray lines have been discovered, such as the 1.157 MeV line from ^{44}Ti or several decay lines from ^{56}Co and ^{57}Co. Gamma-ray lines probe aspects of nucleosynthesis, stellar evolution, and supernova physics that are difficult to access by other means. Additionally, they provide tracers of galactic activity and improve our understanding of the interstellar recycling processes.

The progress will continue. In 2001, ESA's *INTEGRAL* gamma-ray observatory will be launched which is equipped with two gamma-ray telescopes, optimised for high-resolution imaging (IBIS) and high-resolution spectroscopy (SPI) (see `http://astro.estec.esa.nl/SA-general/Projects/Integral/integral.html`). Gamma-ray line astrophysics figures among the prime objectives of this mission. With respect to precedent instruments, the *INTEGRAL* telescopes provide enhanced sensitivity together with improved angular and spectral resolution. In particular, SPI will map gamma-ray lines with a spectral resolution $E/\Delta E \sim 500$, corresponding to Doppler velocities of ~ 600 km s^{-1}. It will provide much more detailed maps of the galactic 511 keV and 1.809 MeV line emissions and determine their line profiles with unprecedented accuracy. Following nucleosynthesis theory, the detection of diffuse galactic gamma-ray line emission from ^{60}Fe decay is expected, and more ^{44}Ti supernova remnants should be discovered.

Further progress is expected from new instrumental concepts, such as a high-resolution Compton telescope (eg. [11,1]) or a crystal lens diffraction telescope [33]. The latter concept has the outstanding capacity of providing extremely high signal-to-noise ratios, leading to unprecedented sensitivities to gamma-ray lines. A first balloon flight for a gamma-ray lens prototype is scheduled for summer 2000 (see `http://www.cesr.fr/~pvb/Claire/index.htlm`). Potentially, a space borne gamma-ray lens telescope may observe an extragalactic Type Ia supernova every few months, making gamma-ray line observations a standard tool for supernova research. Such observations will help to improve our understanding of the supernova phenomena, which is particularly important if supernovae shall be used as standard candles to probe cosmology.

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